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COMBINED MEASUREMENTS WITH THREE-DIMENSIONAL DESIGN INFORMATION VERIFICATION SYSTEM AND GAMMA RAY IMAGING - A COLLABORATIVE EFFORT BETWEEN OAK RIDGE NATIONAL LABORATORY, LAWRENCE LIVERMORE NATIONAL LABORATORY, AND THE JOINT RESEARCH CENTER AT ISPRA

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COMBINED MEASUREMENTS WITH THREE-DIMENSIONAL DESIGN INFORMATION VERIFICATION SYSTEM AND GAMMA RAY IMAGING – A COLLABORATIVE EFFORT BETWEEN OAK RIDGE NATIONAL LABORATORY, LAWRENCE LIVERMORE NATIONAL LABORATORY, AND THE JOINT RESEARCH CENTER AT ISPRA

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ABSTRACT

Oak Ridge National Laboratory (ORNL) and Lawrence Livermore National Laboratory (LLNL) have jointly performed tests to demonstrate combined measurements with a three-dimensional (3D) design information verification (DIV) system and a gamma-ray imager for potential safeguard applications. The 3D DIV system was made available by the European Commission's Joint Research Center to ORNL under a collaborative project between the U.S. Department of Energy and the European Atomic Energy Community (EURATOM). The system is able to create 3D maps of rooms and objects and of identifying changes in positions and modifications with a precision on the order of millimeters. The gamma ray imaging system consists of a 4π field-of-view Compton imaging system which has two fully operational DSSD (Double-Sided Segment Detector) High-Purity Germanium (HPGe) detectors developed at LLNL. The Compton imaging instrument not only provides imaging capabilities, but provides excellent energy resolution which enables the identification of radioisotopes and nuclear materials. Joint Research Center was responsible to merge gamma-ray images with the 3D range maps. The results of preliminary first measurements performed at LLNL demonstrate, for the first time, mapping of panoramic gamma-ray images into 3D range data.

INTRODUCTION

Inspection of complex equipments or plants processing Special Nuclear Materials (SNM) can be a very cumbersome process. A change in the original plant design can suggest that the original purpose of the plant was altered, which can indicate malicious proliferating intentions. Visual inspection is not always a reliable way to identify changes in the plant design. Lately however, Laser radar imagers (lidars) were introduced in the inspection process to identify such changes. These systems are able to create full 3-dimensional maps of the installations. These maps can be tracked in time to determine any design changes. This technology can help the inspection process, but also can miss design

changes that are not directly observable with a laser scanner. This work aims to increase the reliability and efficiency of the inspection process by adding a new sensor to the existing lidar scanners. A gamma-ray detector can provide supplementary information about the type of radioactive SNMs present in the region, but can not determine the position and distribution of all radioactive material in the region. Instead, a spectroscopic gamma-ray imager with a very large field of view has the capability of doing that. Such an imager will provide a direct account of the radioactive SNM inside installations, mitigating the hidden changes in the plant design. The combination of the gamma-ray imager with a lidar can bring the extra benefit of matching the distribution of radioactive material with physical objects, leading to a much more accurate understanding of the safeguarding problem. In the last few years, LLNL has been developing such a spectroscopic gamma-ray imager with large field of view [1]. The imagers employ high resolution semiconductor detectors and are using the Compton camera concept for imaging [2]. Lidar scanners, on the other hand, are already successfully deployed for design verification work. The 3D Design Information Verification (DIV) system used by the JRC is such a lidar scanner able to provide a 3-dimensional map of opaque objects.
We have performed joint measurements with the two systems to demonstrate the added capability of verifying not only physical design of equipment, but also the presence, 3D spatial distribution and type of radioactive isotopes inside the equipment. After a presentation of the two systems in the next two chapters, results of test measurements will be reported in the third chapter.

DESIGN INFORMATION VERIFICATION (DIV) SYSTEM

The 3D DIV system consists of a laser range scanner, dolly, tripod, laptop computer, battery pack, battery charger, and software used for 3D data acquisition, modeling, and scene verification. The 3D DIV system deployed by JRC (see figure 4) is intended to detect changes made in a given installation or track the progression of the construction work in a new plant. This system can determine if an industrial plant corresponds to the original design. It is able to create visual 3D maps of rooms and objects and to identify changes in positions and modifications with a precision on the order of millimeters [3]. The system has been made available to ORNL by JRC under Action Sheet 27 between DOE and EURATOM.

COMPACT COMPTON IMAGER (CCI) SYSTEM

The Compact Compton Imager (CCI) is a gamma-ray imaging prototype developed by LLNL. It employs semiconductor Si(Li) and Ge detectors, and it uses the Compton camera concept for gamma-ray imaging [2]. With such an imaging system, unlike other gamma-ray imagers, the directionality of the photons is not obtained by using collimators, but by measuring the scattering angle and scattering direction of the incident photon in a Compton interaction inside a position sensitive detector. These scattering parameters will “collimate” the photon by restraining the places the photon could have originated to the surface of a virtual cone named *“Compton cone”*. The opening of that cone is determined by the scattering angle θ, and the symmetry axis is determined by the scattering direction (see figure 1).

The main requirement for an efficient Compton imager is excellent granularity, as well as energy and position resolution. *Granularity* represents the capability of the system to separate multiple interactions taking place in the same detection bulk. In the present case, this is achieved by employing detectors with segmented electrodes and using advanced data analysis. The version of the imager used in the present measurements contains two planar double sided segmented (DSSD) Ge detectors. The detectors have a cylindrical shape, with a width of 11mm (see figure 2). Both detectors have electrodes segmented in parallel strips of 2mm pitch. One detector contains 38 instrumented strip segments on each electrode, the other contains 32 instrumented strip segments on each electrode. The detectors are placed in two separate cryostats, 60mm from each other (see figure 3). Each segment channel is digitized by fast Struck Innovative Systems SIS3000 digitizers at 100MHz, with 14 bit resolution. The signal filtering is done in the digital environment.

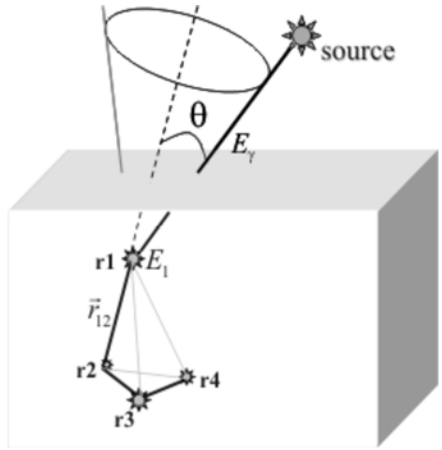

Figure 1 A gamma-ray photon is photoelectrically absorbed in a detector after three Compton scatterings. The positions and energies of all interactions are used to determine the scattering angle, θ, and scattering direction *r12* for the first Compton interaction.

The CCI's good angular resolution and its 4-pi field of view provide great panoramic images of extended sources in medium-range distances, from 3cm to 20 meters. The Compton imaging instrument not only provides imaging capabilities, but provides also an excellent energy resolution of 2 keV, which enables an accurate identification of radioisotopes and nuclear materials. The camera is sensitive to gamma-ray photons of energies between 250keV to several MeVs. We have demonstrated that CCI imagers that include DSSD Si(Li) detectors can be sensitive to energies as low as 140 keV. This low limit makes the system applicable for measurements of 239Pu and 235U. The excellent

Figure 2 Double sided segmented (DSSD) Ge detector inside the cryostat

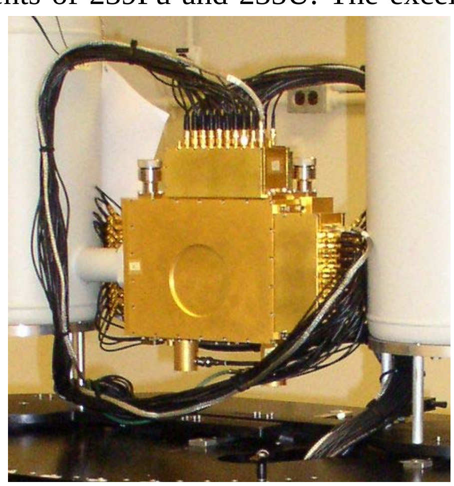

Figure 3 Compact Compton Imager containing 2 DSSD Ge detectors

angular resolution of 2degrees demonstrated by the imaging, combined with the 2keV energy resolution gives this system a competitive advantage over any other existing state-of-the-art system for the kind of application envisioned in this paper.

TEST MEASUREMENTS WITH THE COMBINED DIV-CCI SYSTEMS

The goal of the measurements was to demonstrate the potential gain in monitoring equipment and nuclear materials simultaneously with gamma-ray imaging and the 3D DIV system (see figure 4). Test measurements were performed in Livermore, where mock-up pipes were installed in a laboratory room. An extended Eu-152 line source was hidden inside a mock-up pipe (see figure 5). The source had 70microCi of activity uniformly distributed along its length of 1 meter. The aim of the measurement was to prove the capability of the gamma-ray camera to identify and determine the spatial distribution of the extended source, and subsequently, to merge the gamma-ray image with the 3D range map delivered by the 3D DIV system.

For a better coverage of the objects in the room, the 3D DIV scanner acquired data from 3 different positions. In this way, parts of the objects that would have been shadowed in a single scan, can still be mapped by the other scans. The CCI system acquired gamma-ray

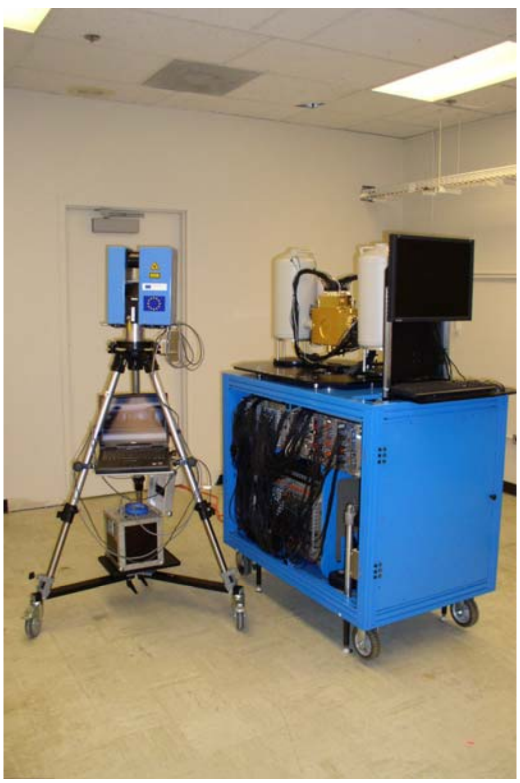

Figure 4 A 3D Design Information Verification (DIV) laser range scanner (left) and a Compact Compton Imager (CCI) gamma-ray camera on a mobile cart (right).

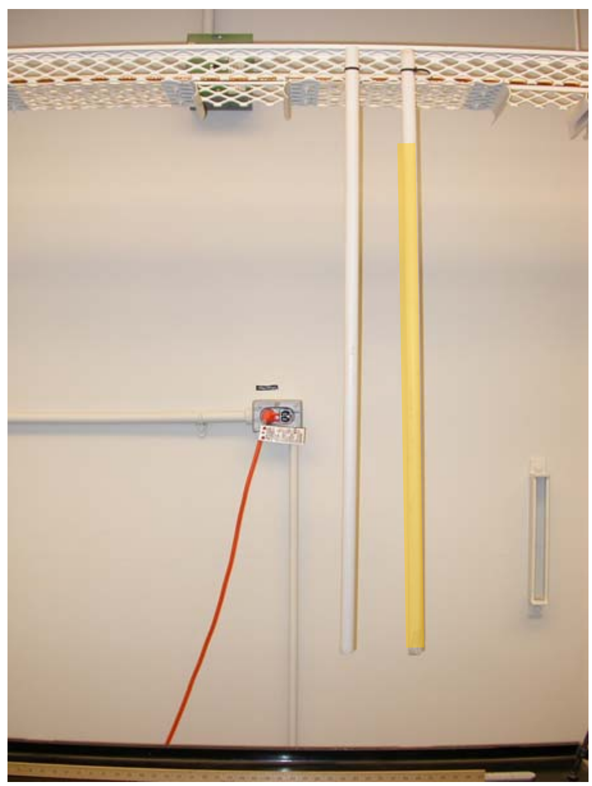

Figure 5 Set-up of two mock-up pipes, one of which contains a hidden Eu-152 line source (yellow-highlighted pipe);

images from 3 different positions, as well. In this case, multiple images were required in order to triangulate the distance from the camera to the radioactive sources. Hence, the third dimension was obtained by triangulating the 2D gamma-ray imaging projections obtained at different positions.

A visual photocamera was used in conjunction with a 360degrees TotalView lens to provide a panoramic picture of the setup. Such a panoramic picture of the measurement room is shown in figure 6. A contour plot of a gamma-ray intensity map as measured from the same point-of-view is superposed on the picture. The photons used in the gamma-ray image were selected within an energy window of 8 keV around the 344keV Eu-152 line. The gamma-ray intensity map was obtained by using an Expectation-Maximization, Maximum Likelihood image reconstruction algorithm.

A zoomed-in image of the source region is shown in figure 7. A good match between the radioactive pipe and high intensity gamma-ray image can be observed. However, the upper part of the radioactive pipe is not accurately represented in the gamma-ray image. The reason for this is the relatively lower efficiency of the CCI system for sources that are closer to the plane going through the middle of the detectors, parallel with the detector electrodes plane.

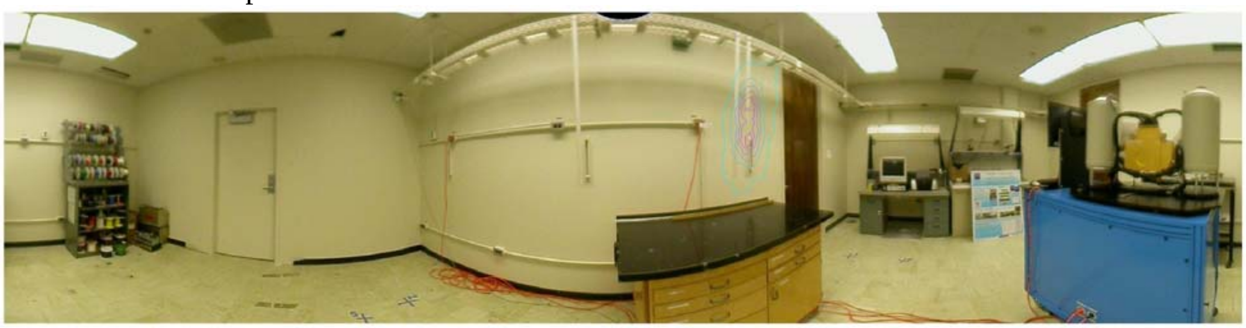

Figure 6 Panoramic image of the experimental room. A 2D gamma-ray map is superposed as a contour plot

Panoramic color visual images were also used to generate color and texture for the 3D range maps obtained with the 3D DIV scanner. Gamma-ray images were then combined with the textured three-dimensional laser range map to directly match the radioactive materials identified by the gamma-ray camera with physical objects. In a data merging test, a 2D gamma-ray image was projected onto the 3D map of objects. Two snapshots of the results can be seen in figures 8 and 9. Projection of the gamma-ray map is represented in the 3D model by the colored surface plots. For visual clarity, the CCI cart was removed from the integrated 3D room model. However, the CCI position is represented by one of the inner coordinate systems superposed on the image. The other coordinate system in the picture represents the position of the panoramic color visual camera. This is the same point from which the virtual scan was obtained using the 3D range data.

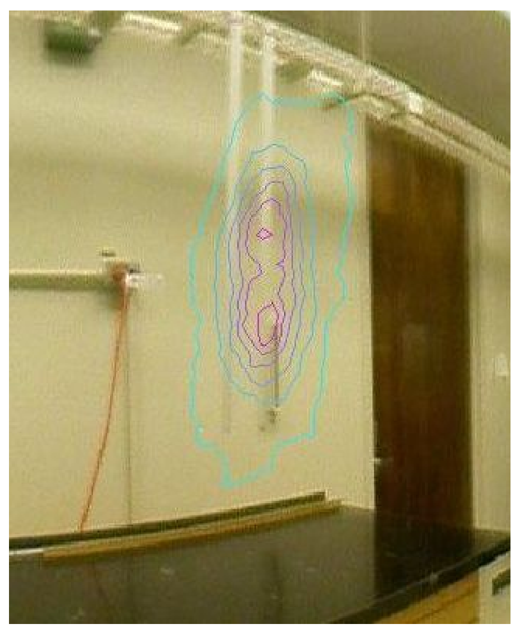

Figure 7 Zoomed-in image of the radioactive region

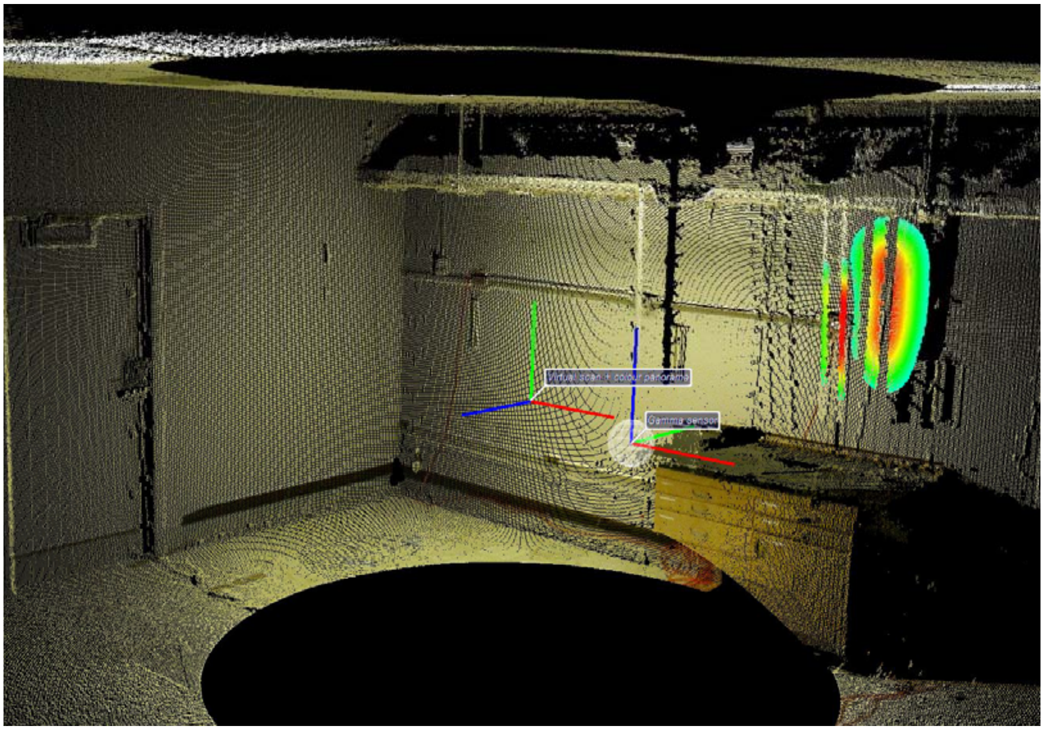

Figure 2 Snapshot of the 3D integrated model of the room. Backprojected hot spots of radioactivity are represented as surface plots superposed onto the virtual scan. The position of the gamma-ray imager is represented by one of the inner coordinate system. Side view.

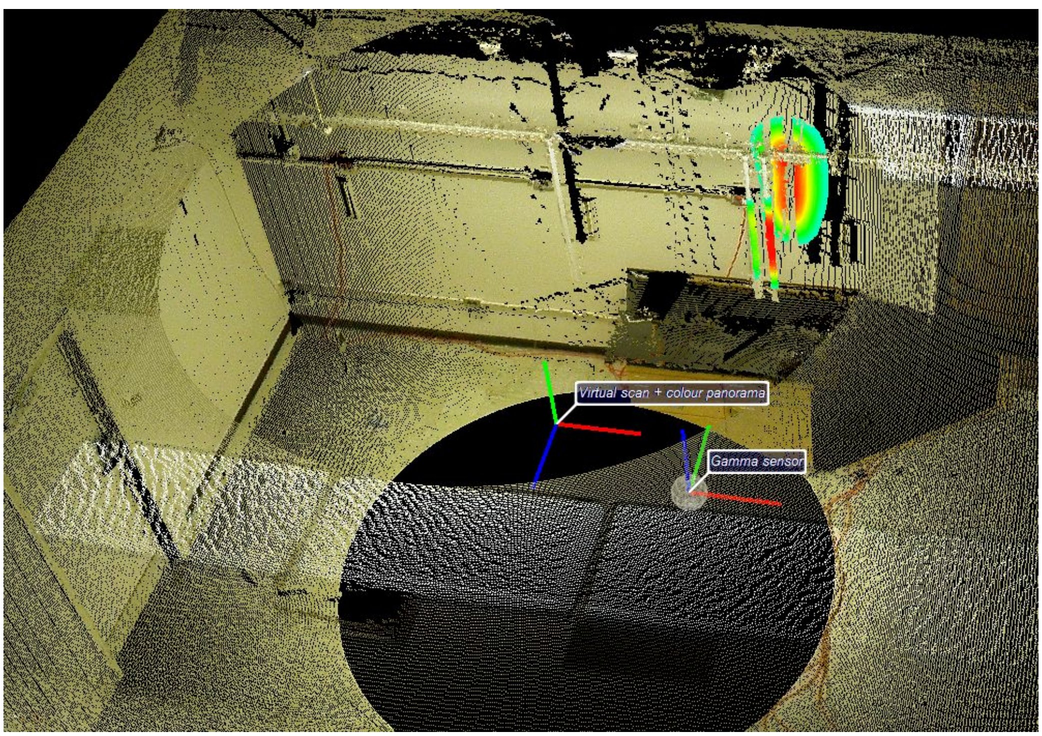

Figure 3 Snapshot of the 3D integrated model of the room. Backprojected hot spots of radioactivity are represented as surface plots superposed onto the virtual scan. The position of the gamma-ray imager is represented by the inner coordinate system. Top view.

One can observe that the gamma-ray image was backprojected both on the pipes, as well as on the back wall. This can create confusion in identifying the radioactive objects, especially when several objects exist in different planes. This confusion can be alleviated by taking gamma-ray images from different positions, and subsequently, by employing a 3D image reconstruction algorithm to combine 2D projections into a 3D gamma-ray map. This image reconstruction process can be significantly helped by using the 3D range data to confine the 3D region with potential radioactivity to the extend of physical objects. Even though still under development, this type of integration between the two sets will potentially improve both processing speed and image accuracy.

CONCLUSIONS

The experiments leveraged two technologies owned respectively by DOE and EURATOM to provide an enhanced 3D DIV tool by combining three-dimensional visual and gamma ray imaging for safeguards applications at facilities under IAEA Safeguards. For the first time, we have presented results of a measurement in which we have combined lidar range data with large field of view gamma-ray images. The DIV-CCI combined system has the potential to greatly improve materials accountability through enabling more accurate holdup and material accumulation measurements. This combined system should also be able to identify changes taking place in time in the plant design, as well as in the distribution and quantity of the nuclear materials. Applications also could exist at enrichment facilities, for IAEA inspection and monitoring purposes. Other uses, such as mapping contaminated equipments will be assessed.

ACKNOWLEDGEMENTS

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